THE UNIVERSITY OF ALBERTA

A FORCE GENERATOR FOR MUSCLE RESEARCH

BY

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, " A Force Generator For Muscle Research ", submitted by Albert J. Chanasyk in partial fulfilment of the requirements for the degree of Master of Science.

TABLE OF CONTENTS

LIST OF DIAGRAMS

ABSTRACT

By studying the transient and frequency response characteristics of small muscle specimens, valuable information concerning their nature can be obtained. To obtain this information a device is required, which is capable of producing a force or displacement linearly related to an input electrical signal and independent of the compliance and damping of the specimen. This thesis deals with the design, development, and evaluation of such a device. The device which consists of a force producing element, a position sensing unit, a rate sensing unit, and a force transducer, was operated to determine its open loop characteristics. After compensating the system to improve the performance, the system was operated closed loop with positional feedback to determine the passive transfer function of the sartorius leg muscle of a frog. Finally the system was operated closed loop, with force feedback and then with positional feedback, to evaluate the system performance.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

1.1 OBJECT

An earlier attempt to design an apparatus capable of appling small sinusoidal input forces to various muscles and measuring the displacement response, was made by E. Karpinski (2). This device, which utilized a Sanborn Pen motor as the force producing unit and a Statham type G1-4-250 unbonded Constantan strain gauge bridge as the force transducer, failed to meet the bandwidth and steady state error requirements. As a result, satisfactory results could not be obtained. Also it was uncertain if the muscle frequency response results obtained in this work were completely independent of the system characteristics.

The objective of this project was the design, development, and evaluation of a control system which would utilize different mechanical components and meet the necessary requirements. The system must be capable of producing a force or displacement linearly related to an electrical input signal and independent of the compliance and damping of the specimen.

The secondary objective of this project was to obtain the passive transfer function of the sartorius leg muscle of a frog and, by comparison, to determine if the results obtained by Karpinski were completely independent of the system characteristics.

1.2 SYSTEM REQUIREMENTS AND SPECIFICATIONS

The prior work by E. Karpinski (2) indicated that in order that useful results be obtained the system should have a bandwidth of approximately one hundred hertz and that the steady state error be small to eliminate the need for calibration. Also the available applied force should be of low distortion. His suggested main specifications, as the minimum requirements of the final system, were chosen as the requirements for this project.

These specifications were:

(1) Driving force range 9.8×10^{-5} newton (10mg) to 9.8×10^{-2} newtons (10gm) peak to peak force.

(2) Bandwidth D.C. to 100 hertz and,

(3) Steady state error less than 2 percent.

1.3 DESIGN

The system configuration and the components used to meet the above specications are shown in figure 1 and 2. A high system gain and negative feedback were used to compensate for non-linearities. In order to minimize noise input into the system, mercury batteries were used for critical voltage sources.

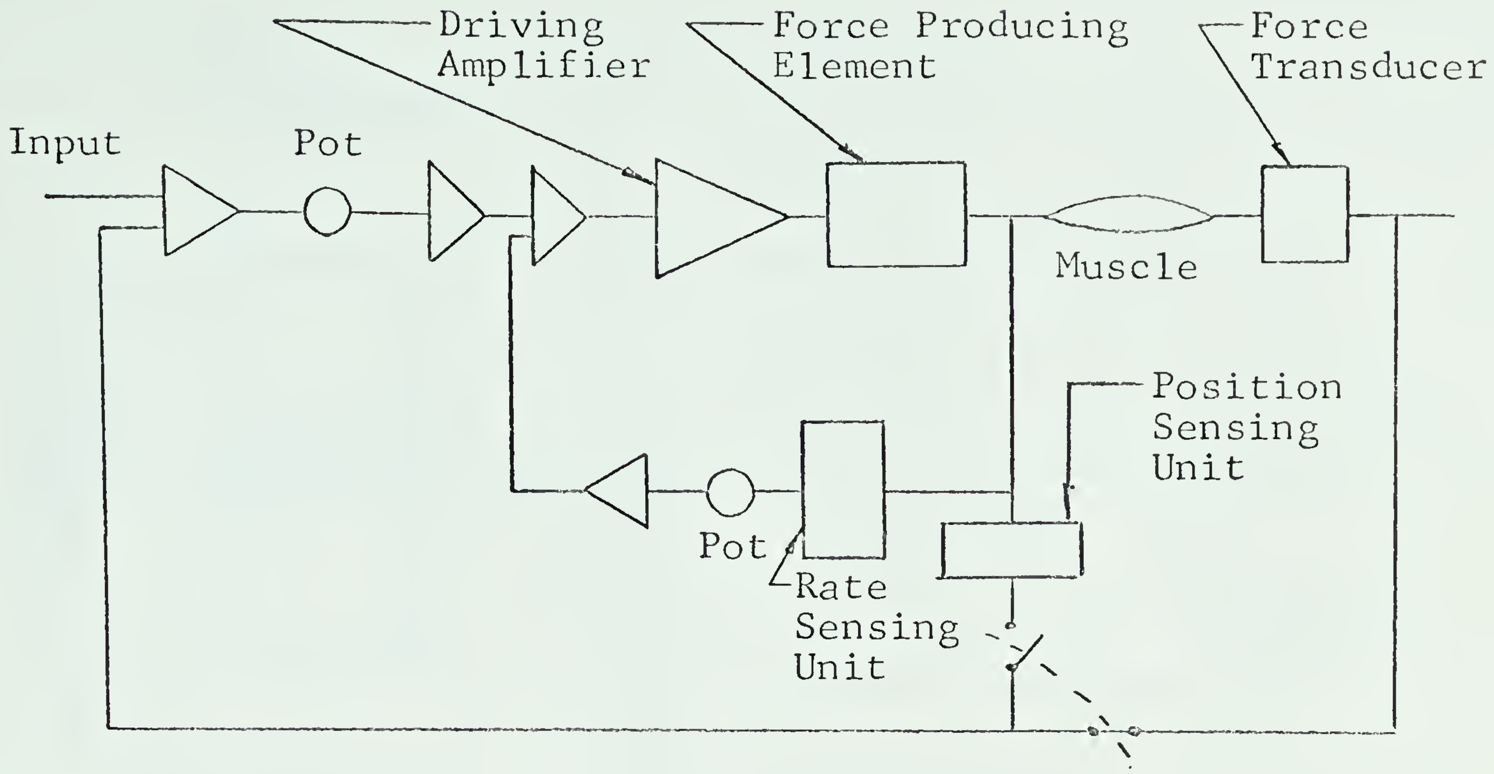


figure 1.

BLOCK DIAGRAM OF THE FORCE CONTROL SYSTEM

1.4 COMPONENTS

(a) FORCE PRODUCING ELEMENT

The force producing element, shown in figure 2, functions on the principle of an electrodynamic loudspeaker and consists of a speaker magnet assembly with the gap increased to .070 inches to accommodate a 1.875 inch diameter coil. The gap strength of the magnet is 12,000 gauss and the resistance and inductance of the coil are 21 ohms and 2.7 millihenries respectively. The coil is mounted on a .063 inch diameter brass tube and supported in nylon bearings mounted on each end of the magnet assembly. The allowable axial movement was set to .10 inches. The brass tube was plated with gold and in turn with rodium to reduce friction.

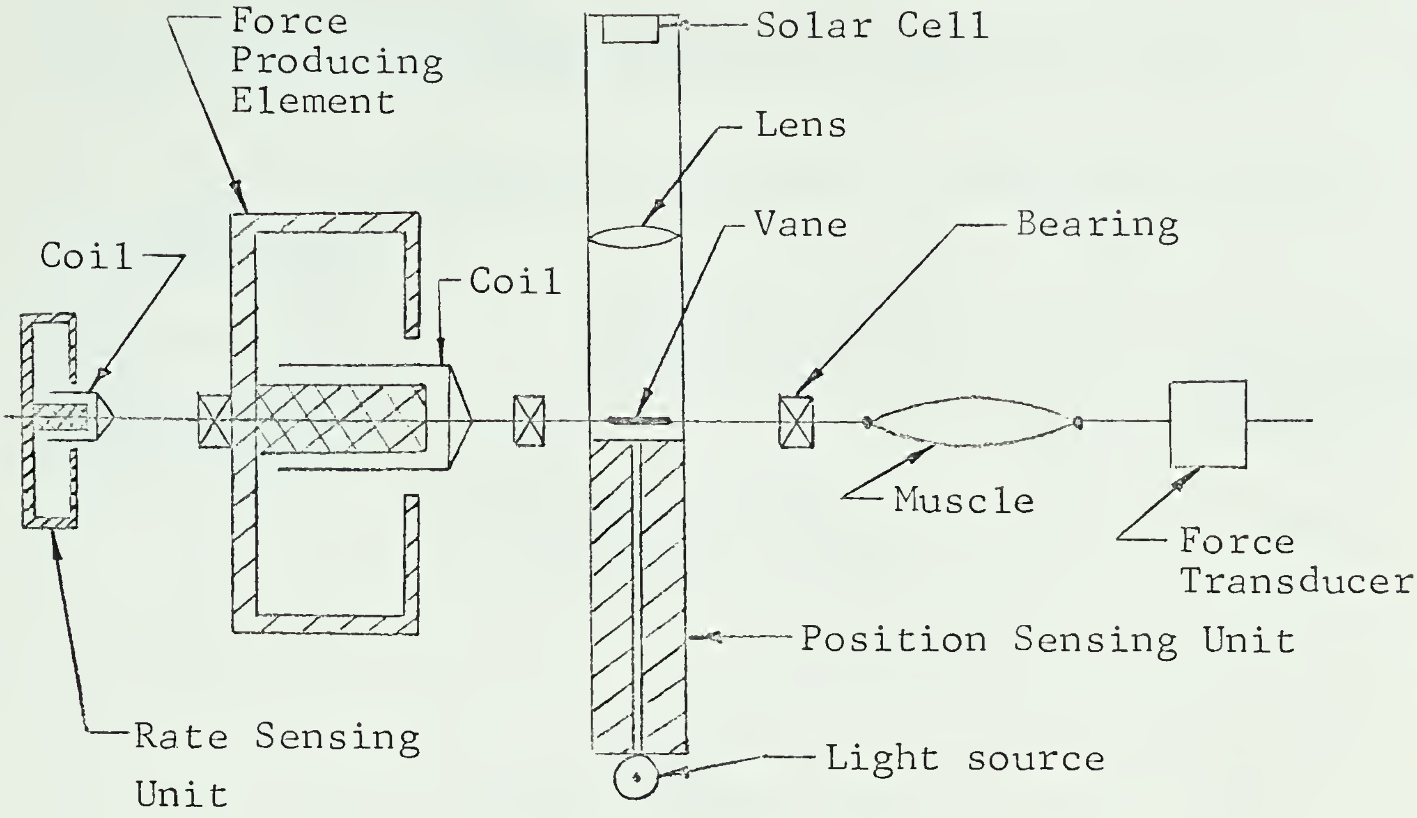


figure 2.

MECHANICAL ARRANGEMENT OF THE SYSTEM

(b) FORCE SENSING UNIT

The force sensing unit, shown in figure 3, consists of a Pixie 8101 mechanical and electrical transducing element clamped in a mechanical and electrical clamp. A small hook was cemented with epoxy to the transducing element to facilitate the attachment of the muscle.

Since the transducing element was light sensitive, the total assembly, except for a small hole for the hook, was masked to prevent unwanted electrical noise.

When a small force is applied to the hook the transducer's beam bends loading the resistive element. This results in a corresponding linear change in resistance.

The specification listed by the manufacturer for the Pixie 8101 transducing element are shown in figure 4.

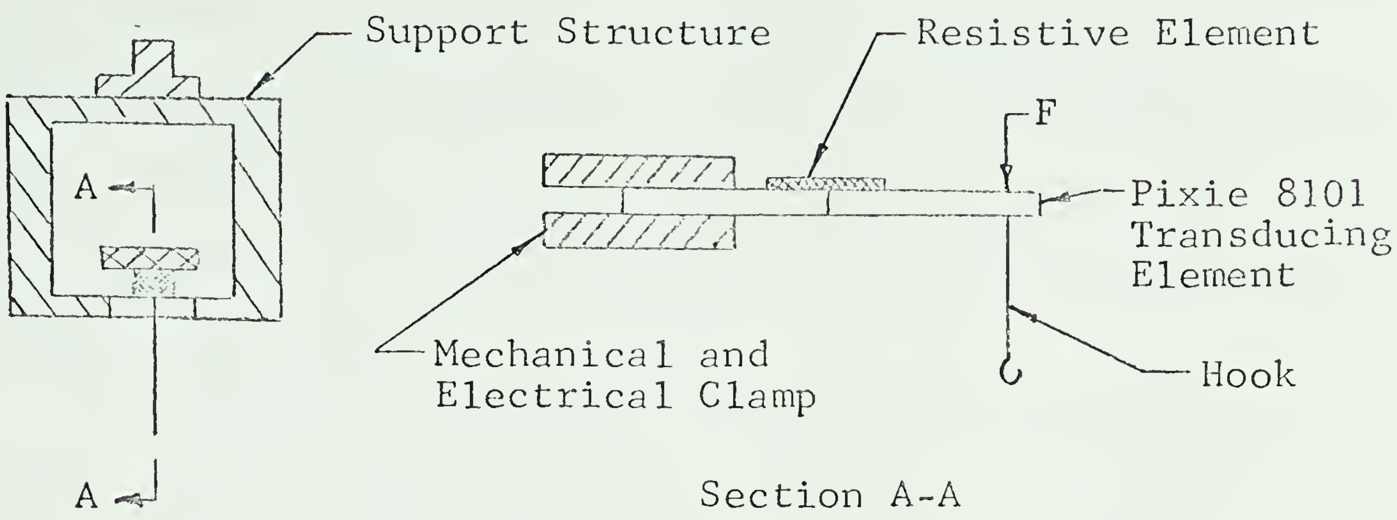


figure 3
FORCE SENSING UNIT

Sensitivity (min) R/R/gm. @ F	1.4 %
Noise (μv RMS) 300 Hz to 5K Hz	4
Temperature Range (Operating)	-18 to +74°c
Compliance μ"/gm. @ F	55
Proof Force	±40 gms.@ F
Linearity	±1 % to 10 gms. @ F
Resistance vs. Temperature	+0.75 % /°c nominal

figure 4
SPECIFICATIONS FOR THE PIXIE
8101 TRANSDUCING ELEMENT

(c) FORCE TRANSDUCER

The force transducer, shown in figure 5, consists of a Pixie mechanical to electrical transducing element and a force sensing unit operated as the input and feedback resistors, respectively, of an operational amplifier. The output of this operational amplifier and a bias voltage are summed to give zero output for no load.

The change in resistance of the force sensing unit, with the application of a force, results in a change in gain of the amplifier and a corresponding change in the output voltage. This configuration also gives a first order compensation for any temperature changes.

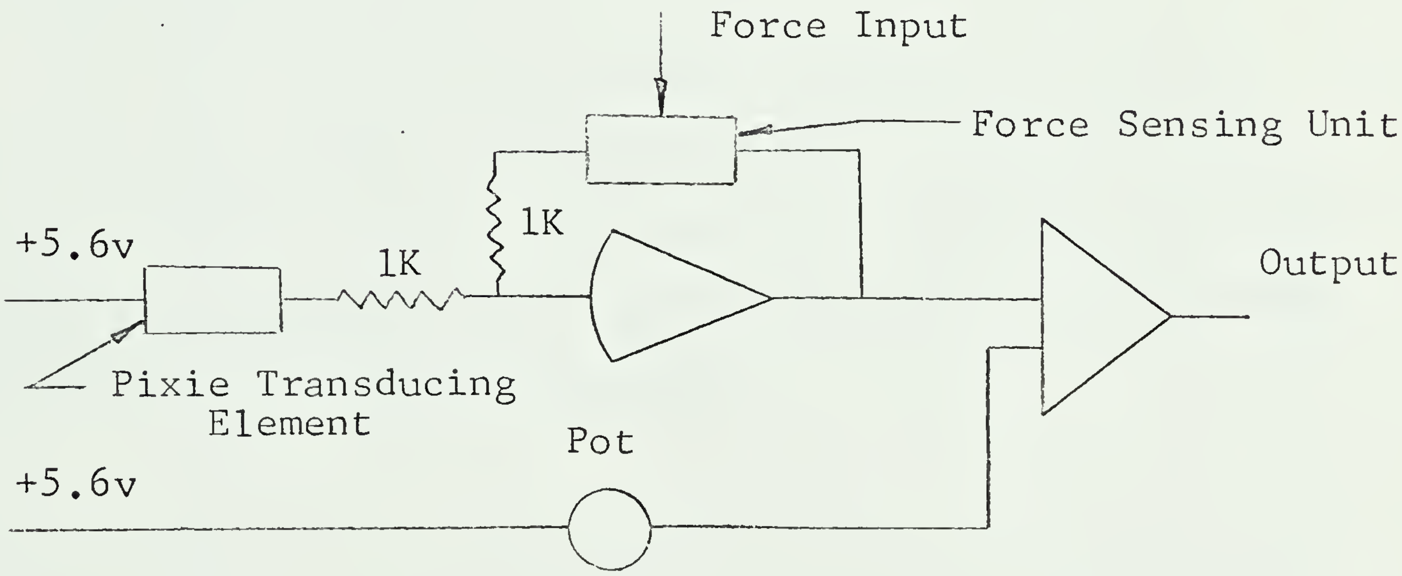


figure 5

FORCE TRANSDUCER SCHEMATIC

The relationship between the input force and the force transducer output voltage is given by the equation:
$F = 14.3\ E$, where F is measured in gms. and E is measured in volts.

(d) POSITION SENSING UNIT

The position sensing unit, shown in figure 2, consists of a vane which impedes a rectangular beam of light directed on a solar cell. The vane is attached to the shaft of the force producing element. Any change in position of the vane results in a linear change in the area of photo cell illumination. This results in a corresponding linear change in output voltage across the solar cell resistor. The time constant of the solar cell was measured to be 8×10^{-5} sec.

(e) RATE SENSING UNIT

The rate sensing unit, shown in figure 2, consists of a coil and magnet assembly similiar to the force producing element. As the coil moves axially in the magnetic field, an output voltage is generated which is proportional to the rate of change of position.

CHAPTER II

OPEN LOOP CHARACTERISTICS

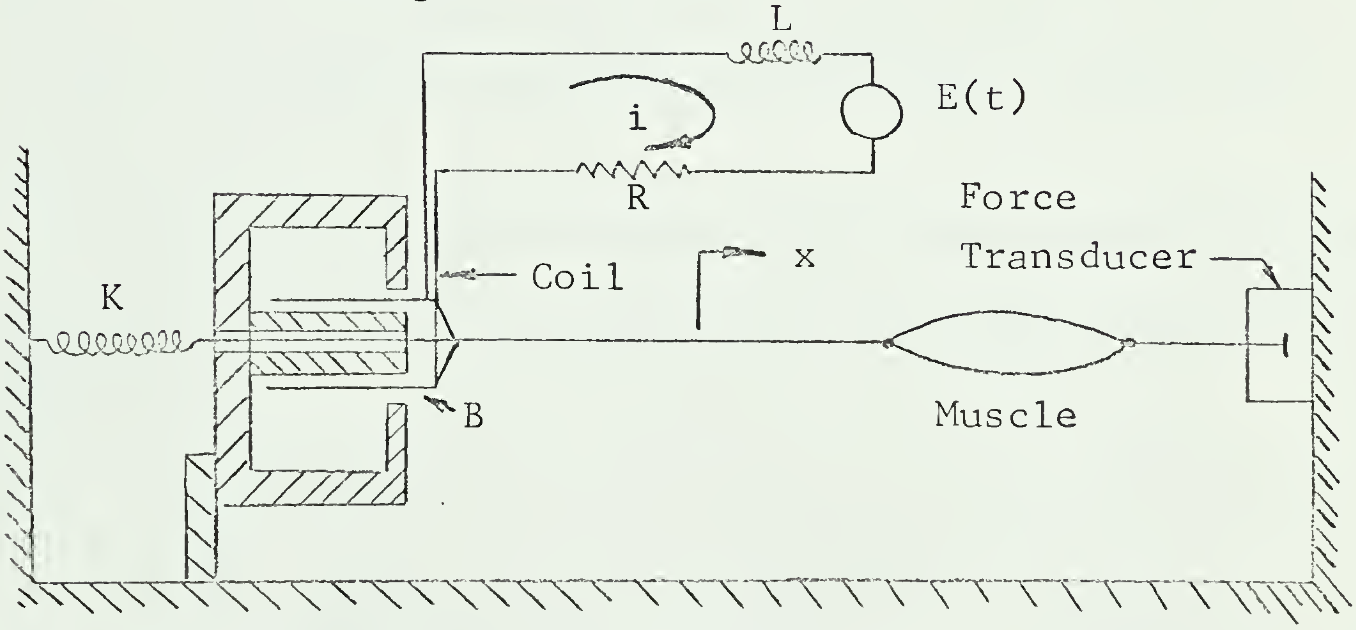
2.1 ANALYTICAL DERIVATION

Considering the system schematic in figure 6, where E(t) is the input voltage function, the follow equations can be written:

$$f = lBi \text{ ....} 2.1$$

$$E = Ri + L\dot{i} + lB\dot{x} \text{ ......} 2.2$$

$$f = \frac{W}{g}\ddot{x} + f' - f'' \text{ ......} 2.3$$



R = coil resistance

L = coil inductance

i = coil current

K = spring constant

B = flux density

l = wire length in the gap

x = displacement of the shaft

figure 6

SYSTEM SCHEMATIC

Where:

W = weight of the moving assembly

f' = force exerted on the coil by the spring = Kx

f'' = the force exerted on the coil by muscle

f = the force produced by the force producing element

The difference between the force f" and the force applied to the force sensing unit is dependent on the effective mass and compliance of the muscle. If the mass of the muscle is small and if the apparatus is used only for frequencies below the resonant frequency of the muscle, the force due to the mass and acceleration can be neglected. Thus it can be assumed for this analysis that the force f" is equal and opposite to the force measured by the force sensing unit.

Taking the Laplace transforms and defining the transfer function of the muscle as G(s) the following equations are obtained:

$$F(s) = lBI(s) \qquad \text{2.4}$$

$$E(s) = RI(s) + Ls\,I(s) + lBsX(s) \qquad \text{2.5}$$

$$F(s) = \frac{Ws^2X(s)}{g} - F''(s) + F'(s) \qquad \text{2.6}$$

$$G(s) = \frac{F''(s)}{X(s)} \qquad \text{2.7}$$

Using the above equations the signal flow graph shown in figure 7 can be drawn.

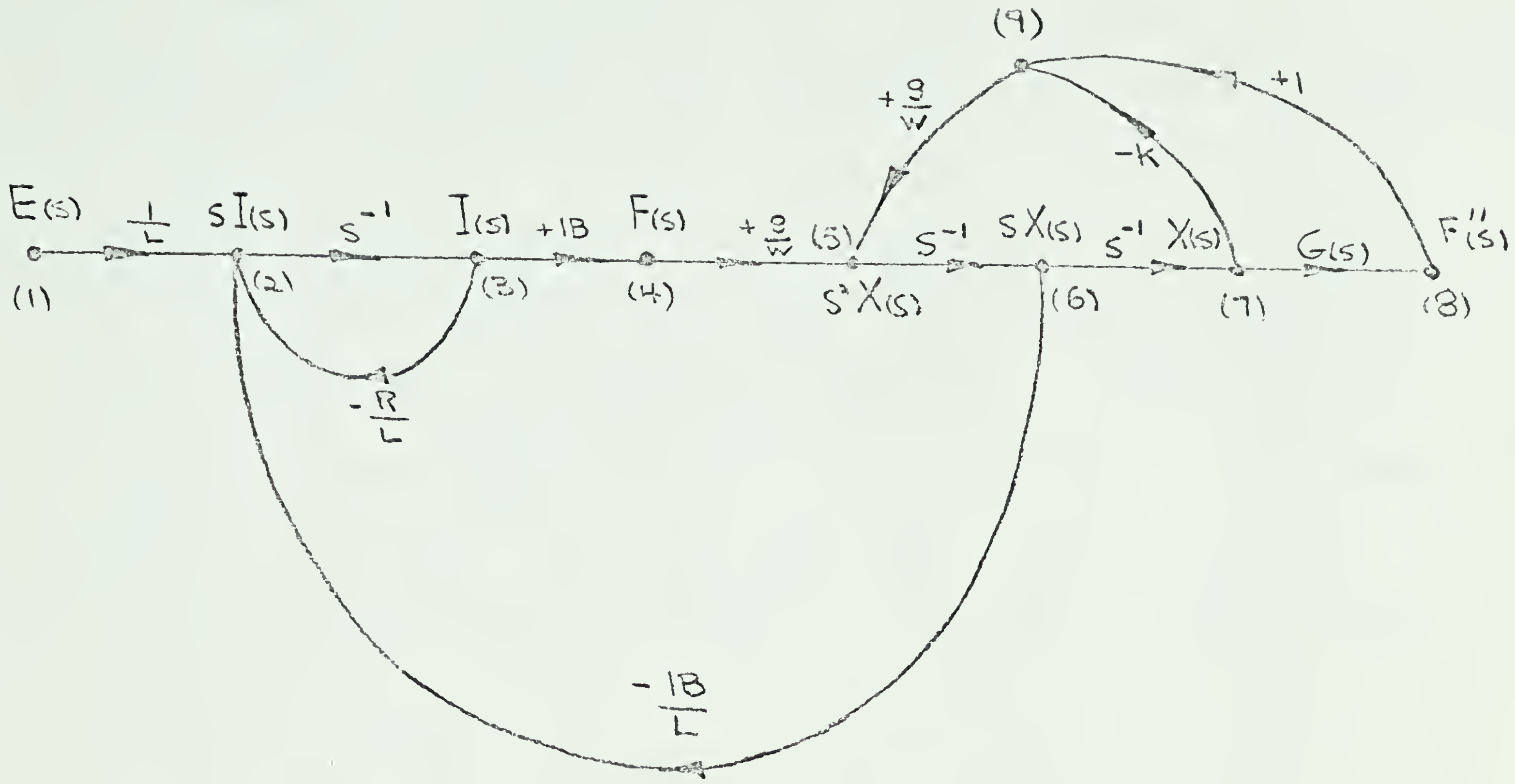


figure 7

SIGNAL FLOW GRAPH OF THE SYSTEM

Considering the signal flow graph, shown in figure 7, it can be seen that the inputs to node 9 are -KX(s) and +F"(s). If the value of K is increased, making -KX(s) dominant in comparison with F"(s), the feedback loop 9-8 can be neglected and the system transfer function can be approximated very accurately as $\frac{X(s)}{E(s)} \cdot G(s)$. The expression for $\frac{X(s)}{E(s)}$ can be obtained experimentally independent of G(s).

By appling Masons rule to the signal flow graph and neglecting the feedback loop,the following expression can be obtained.

$$\frac{X(s)}{E(s)} = \frac{g(lB)^2}{WLs^3 + WRs^2 + g(KL + lB)s + KRg} \qquad \text{...........} \ 2.8$$

2.2 EXPERIMENTAL MEASUREMENTS

Using an elastic band with a spring constant of approximately 48gm./cm. and arranging the system as shown in figures 6 and 8 the open loop characteristics were obtained. To drive the force producing element, an amplifier of low output impedance was used. The circuit diagram for this amplifier can be found in Appendix I. The frequency response curves $\frac{X(s)}{E(s)}$ for cases with and without a coupling muscle were found. On comparison they differed little; the curves are shown in figure 9. The shape of the curve indicates a zero order system with corner frequencies at 25, 566, and 6900 radians/sec. The complete transfer function of the system was found to be:

$$\frac{X(s)}{E(s)} = \frac{21.0 \times 10^6}{(s+25)(s+566)(s+6900)} \quad ....2.9$$

Equation 2.9 is of the same general form obtained analytically in section 2.1

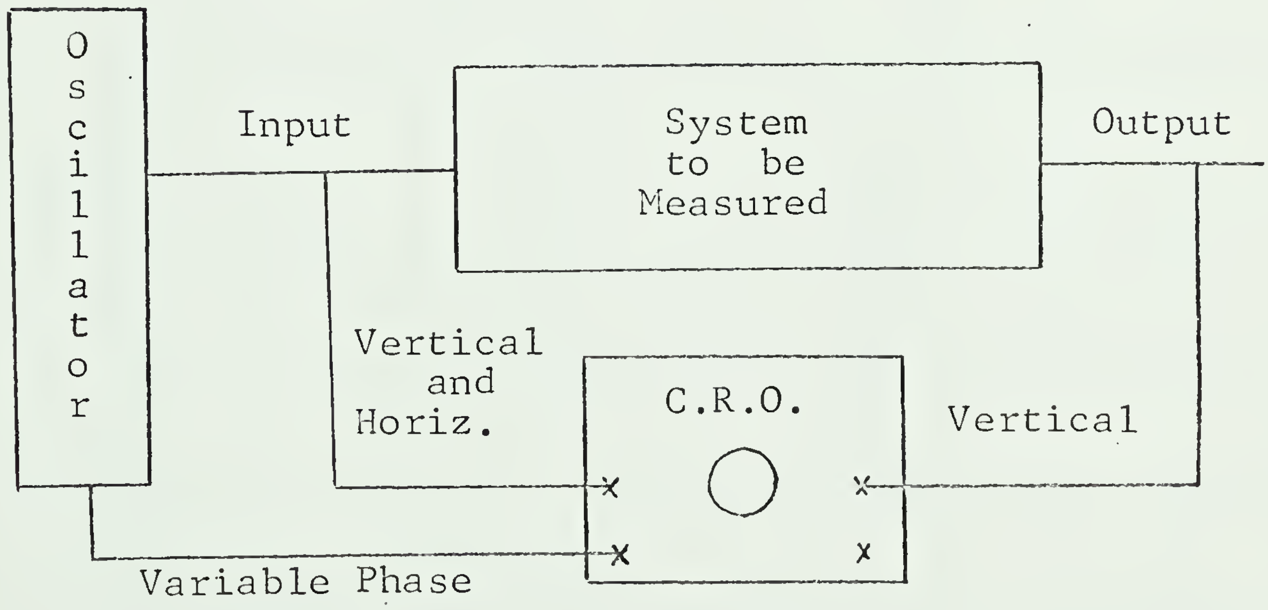


figure 8

EXPERIMENTAL ARRANGEMENT FOR DETERMINING FREQUENCY RESPONSE CHARACTERISTICS

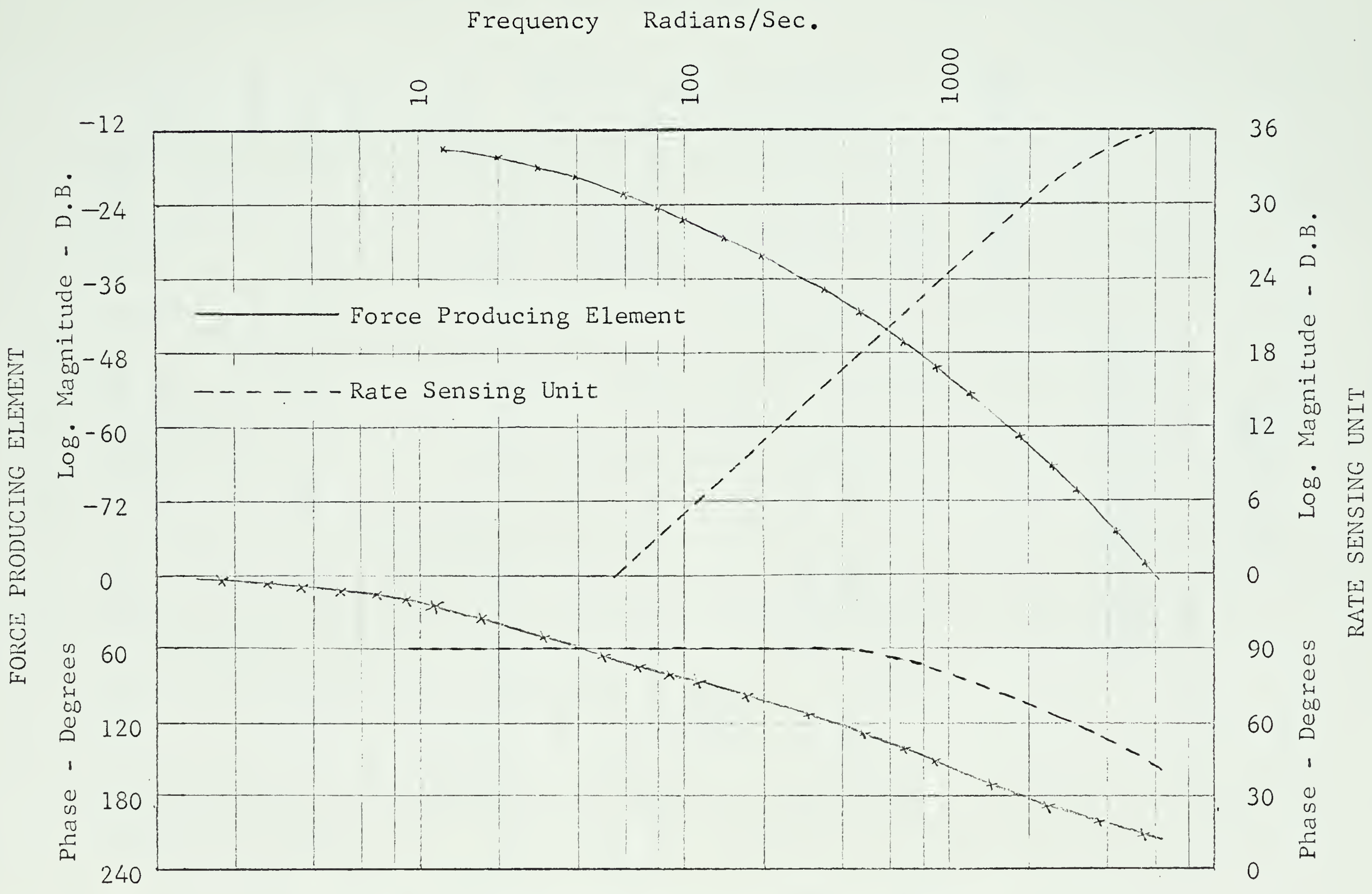


figure 9 OPEN LOOP FREQUENCY RESPONSE CURVES

CHAPTER III

POSITION CONTROL SYSTEM

3.1 GENERAL

To obtain a system capable of applying a force linearly related to an electrical input signal, the apparatus can be operated closed loop with force feedback. But since the transfer function of the coupling muscle is an integral part of the open loop transfer function $\frac{F''(s)}{E\ (s)}$, the closed loop performance cannot be predicted, and the effect of any compensation cannot be accurately determined before the frequency response of the muscle is known.

By operating the apparatus closed loop with positional feedback a position control system can be obtained. The performance of this system is virtually independent of the muscle characteristics and can be compensated if necessary. A small sinusoidal displacement can be applied to the muscle and the output force can be monitored to determine the mechanical small signal transfer function of the whole muscle. Once this information is obtained, the system can be compensated and operated as a force control system.

3.2 COMPENSATION DESIGN

The system was arranged as shown in figure 10 and the frequency and transient responses were determined. With a gain of 500 the transient response was oscillatory with an overshoot of 62 percent. The frequency response curve, of position verus input voltage , shown in figure 15 exhibited an 11 db peak at 200 hertz.

To improve the performance, rate feedback compensation was used. It is necessary to compensate the system only once since the transfer function $\frac{X(s)}{E(s)}$ is independent of the muscle characteristics. Thus this system can be used for virtually any type of small muscle.

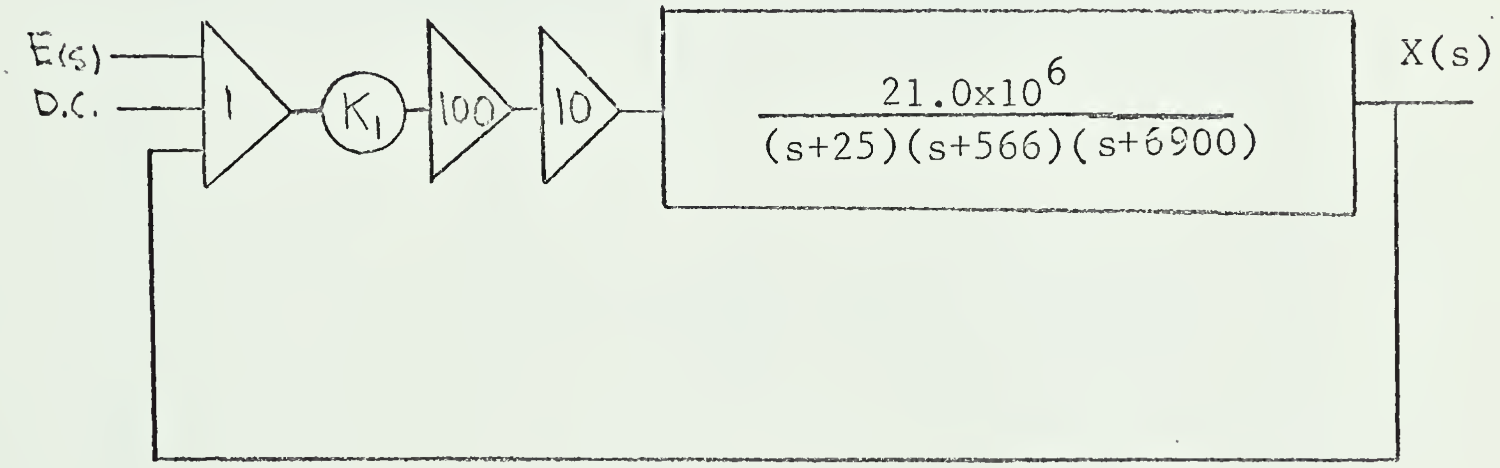


figure 10

BLOCK DIAGRAM OF THE UNCOMPENSATED

POSITION CONTROL SYSTEM

To obtain the characteristics of the rate sensing element, the system was operated open loop and the position and rate signals were monitored. The frequency response curves shown in figure 9 were obtained and the transfer function was found to be:

$$\frac{P(s)}{X(s)} = \frac{93.5s}{(s+5000)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

where P(s) is the Laplace transform of the output from the rate sensing unit.

The block diagram and the root contours for the compensated system are shown in figures 11 and 12 respectively.

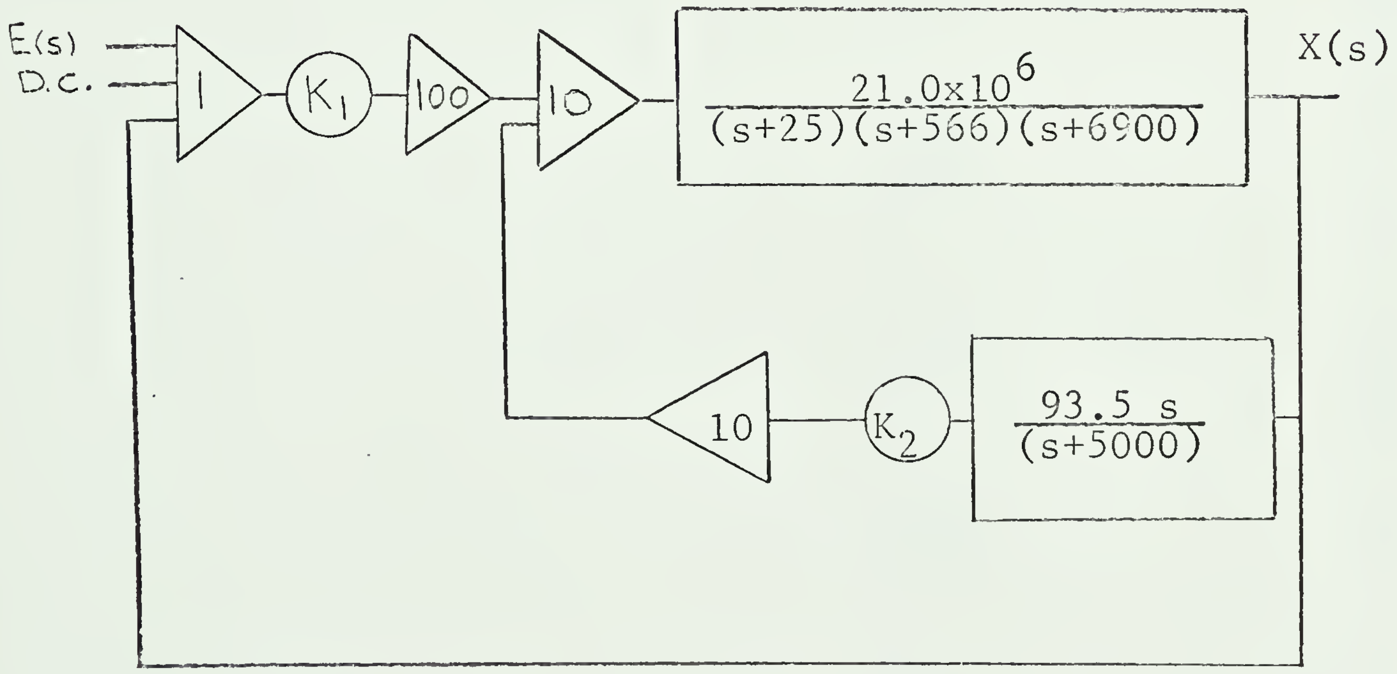


figure 11

BLOCK DIAGRAM FOR THE COMPENSATED

POSITION CONTROL SYSTEM

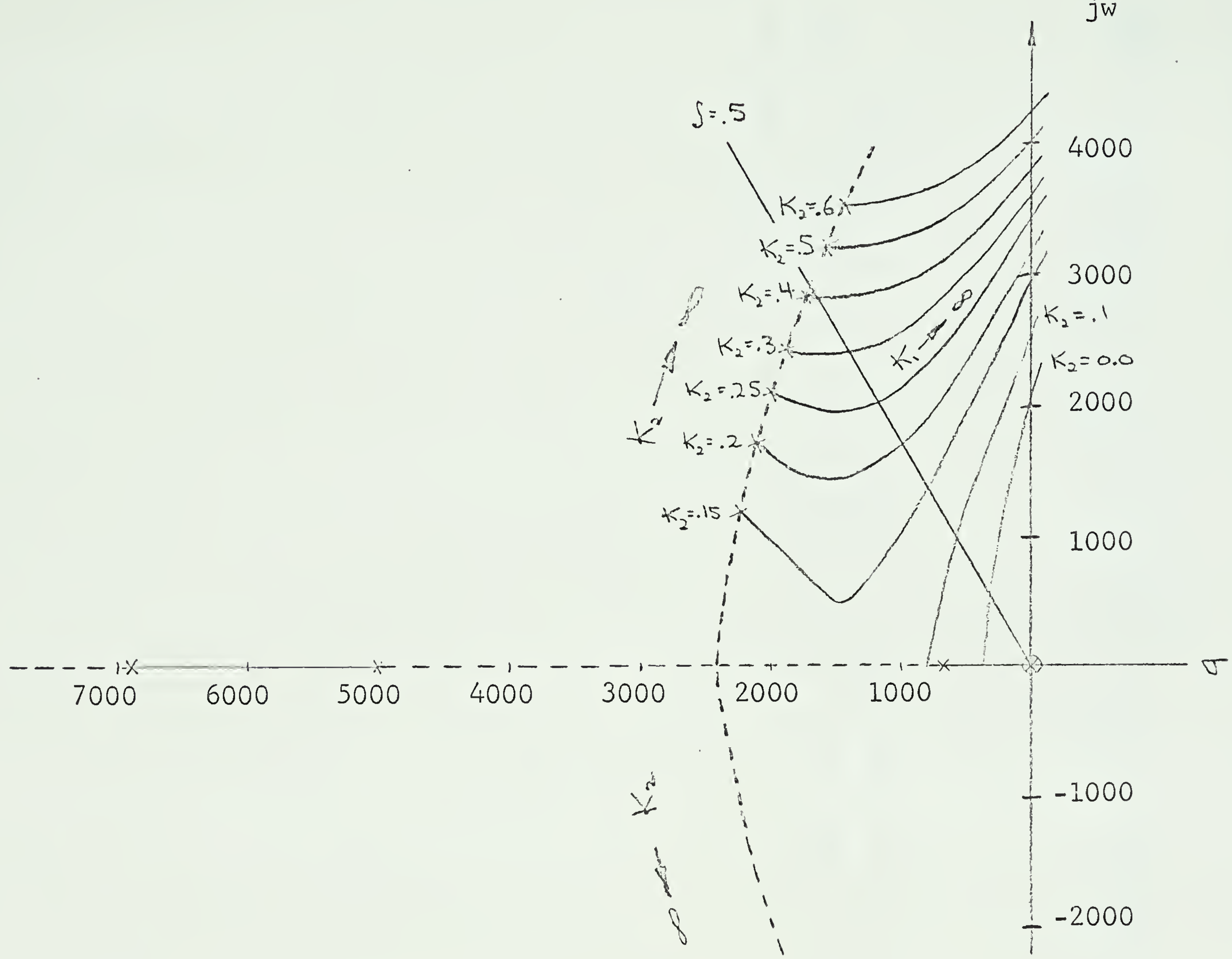


figure 12 ROOT CONTOURS FOR THE COMPENSATED POSITION CONTROL SYSTEM

The closed loop transfer function for the compensated system is:

$$\frac{X(s)}{E(s)} = \frac{21\times10^{9}K_1(s+5000)}{((s+25)(s+566)(s+6900)+21\times10^{9}K_1)(s+5000) + 196\times10^{9}K_2 s} \qquad \text{.......................3.2}$$

Setting K_1 to 0.5 and K_2 to 0.2 and using the arrangement in figure 8 the closed loop position verus input voltage frequency response curves shown in figure 15 were obtained.

CHAPTER IV

MUSCLE TRANSFER FUNCTION MEASUREMENTS

4.1 PROCEDURE

To obtain the transfer function $\frac{F''(s)}{X(s)}$ of a passive sartorius leg muscle the system was operated closed loop with positional feedback. The muscle was dissected from a freshly killed frog and the tendons were tied with thread and attached to the apparatus. To minimize the effects of any building vibrations the apparatus was supported on a foam rubber pad.

Using the experimental arrangement in figure 13 a D. C. signal was applied to the system to prestretch the muscle. A sinusoidal input was then applied and the displacement (input), force (output) and the phase shift were measured. These measurements are independent of the system characteristics since both the input and output of the muscle were measured. Measurements were taken over a frequency range from .01 to 350 hertz. During the tests the preparation was kept moist by continual application of Ringer's solution.

To eliminate errors due to non-linearity of the compliance of the muscle and to obtain a linear transfer function, the force was kept small and constant over the frequency range(2). This was accomplished by varying the system input.

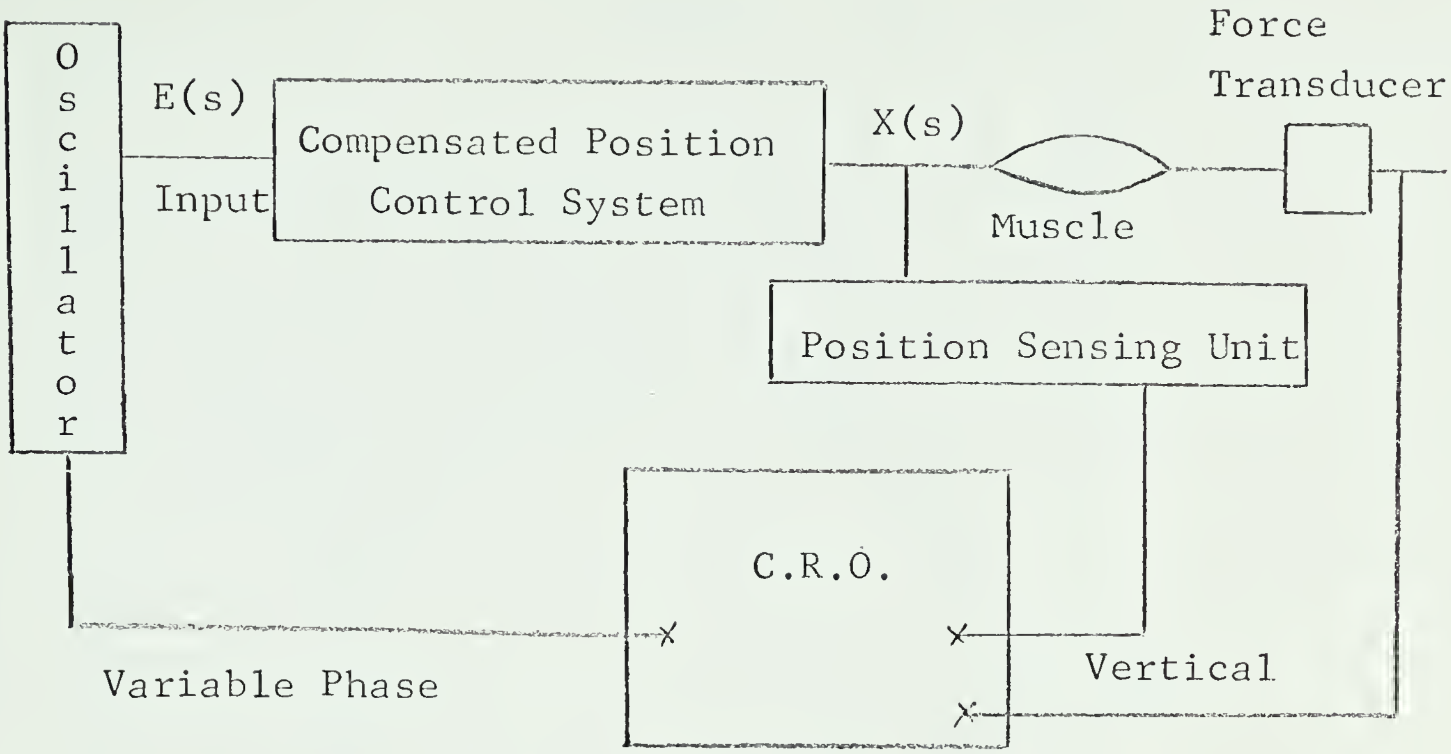


figure 13

EXPERIMENTAL ARRANGEMENT FOR DETERMINING THE MUSCLE TRANSFER FUNCTION

4.2 RESULTS

The procedure described in 4.1 was carried out on two sartorius muscles weighing approximately 150 mg and 130 mg and prestretched to a test length of 1.13 times the relaxed length. The force magnitude was kept constant at approximately 9.8×10^{-3} newtons peak to peak.

Although the results summarized in figure 14, when compared with the response of a lead network, have the same general shape; they do not represent any simple linear transfer function. The maximum slope of the log. magnitude curve is only 10 db per decade and the total phase change is minimal.

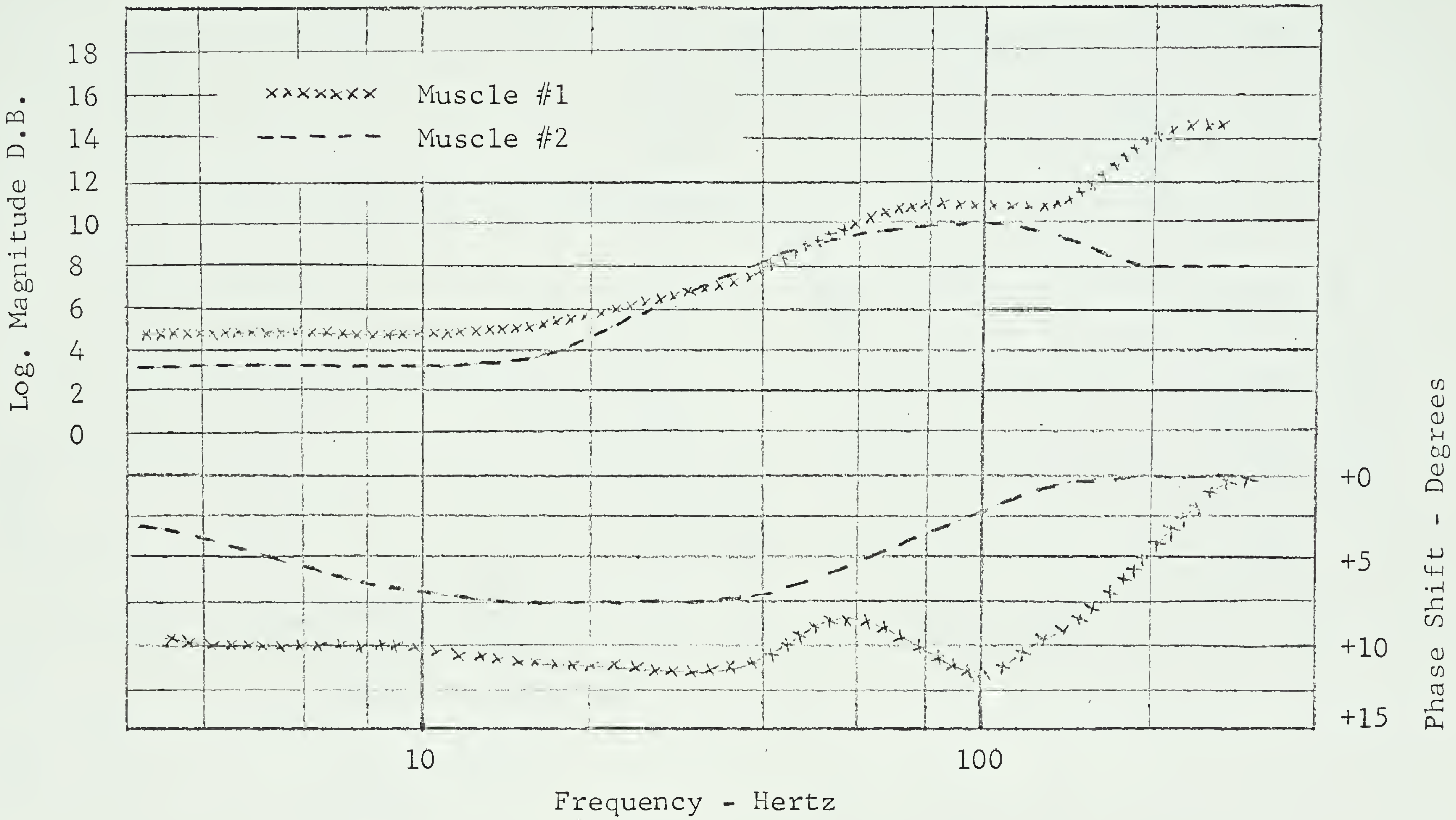


figure 14 MUSCLE FREQUENCY RESPONSE CURVES

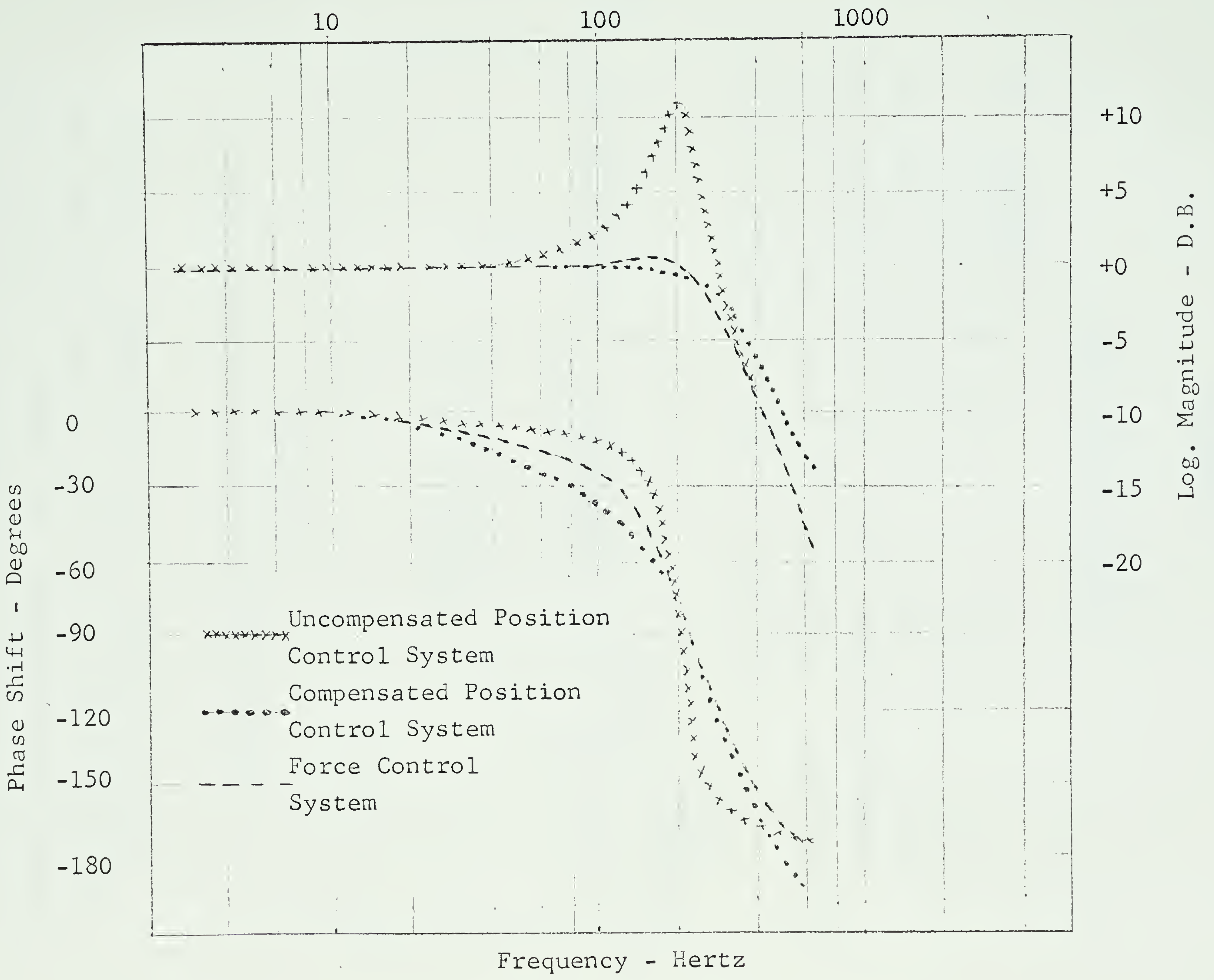


figure 15 CLOSED LOOP FREQUENCY RESPONSE CURVES

CHAPTER V

FORCE CONTROL SYSTEM

5.1 GENERAL

To operate the apparatus as a force control system, the system was arranged closed loop with force feedback and a sartorius muscle was coupled between the force producing device and the force transducer. A block diagram of the arrangement is shown in figure 16.

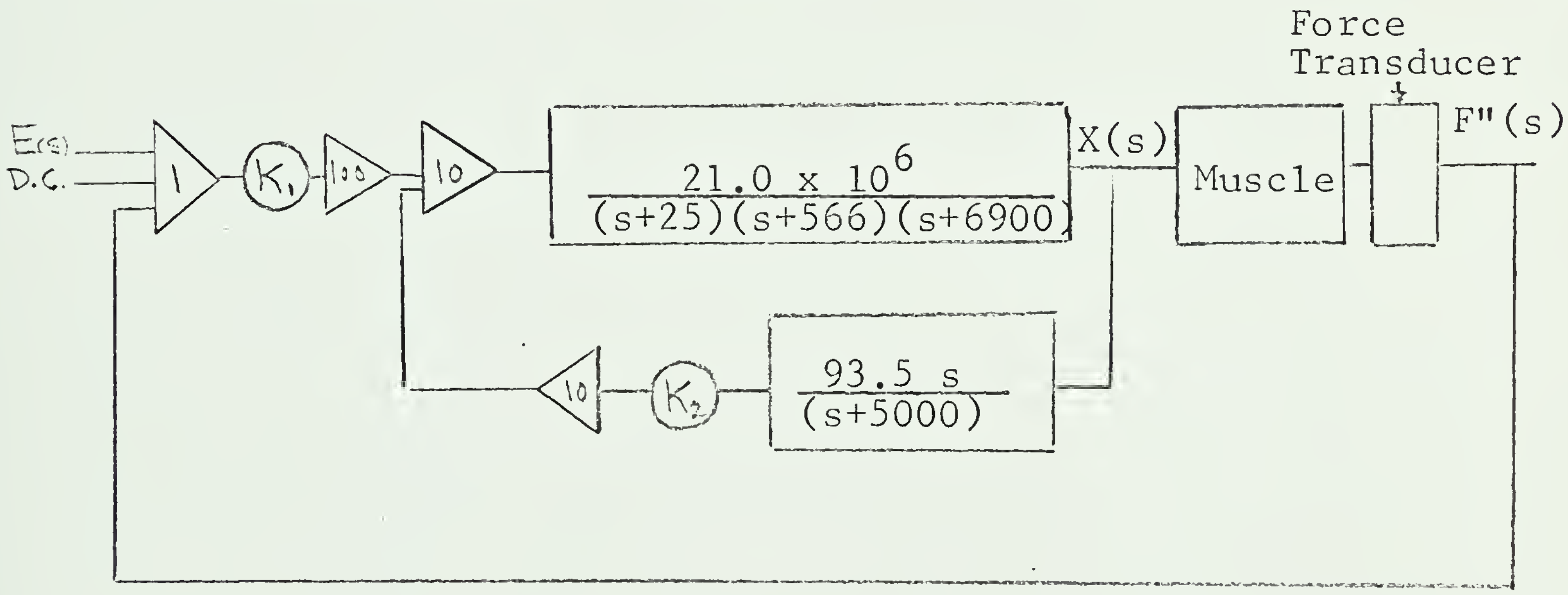


figure 16

A BLOCK DIAGRAM OF THE FORCE CONTROL SYSTEM

Additional compensation was not required since the closed loop performance was adequate to meet the specification outlined in section 1.2 . This will not in general be true for all muscles used with the apparatus since the

closed loop transfer function of the system is dependent on the muscle characteristics.

Setting K_1 to 0.15 and K_2 to 0.2 and using the experimental arrangement in figure 8 the force verus input voltage frequency response curves shown in figure 15 were obtained.

CHAPTER VI

EVALUATION OF THE SYSTEM

6.1 WITH POSITION FEEDBACK AND UNCOMPENSATED

(A) TRANSIENT RESPONSE

With K_1 set to 0.5, a 5 hertz square wave was applied to the closed loop system shown in figure 10. The response is shown in figure 17.

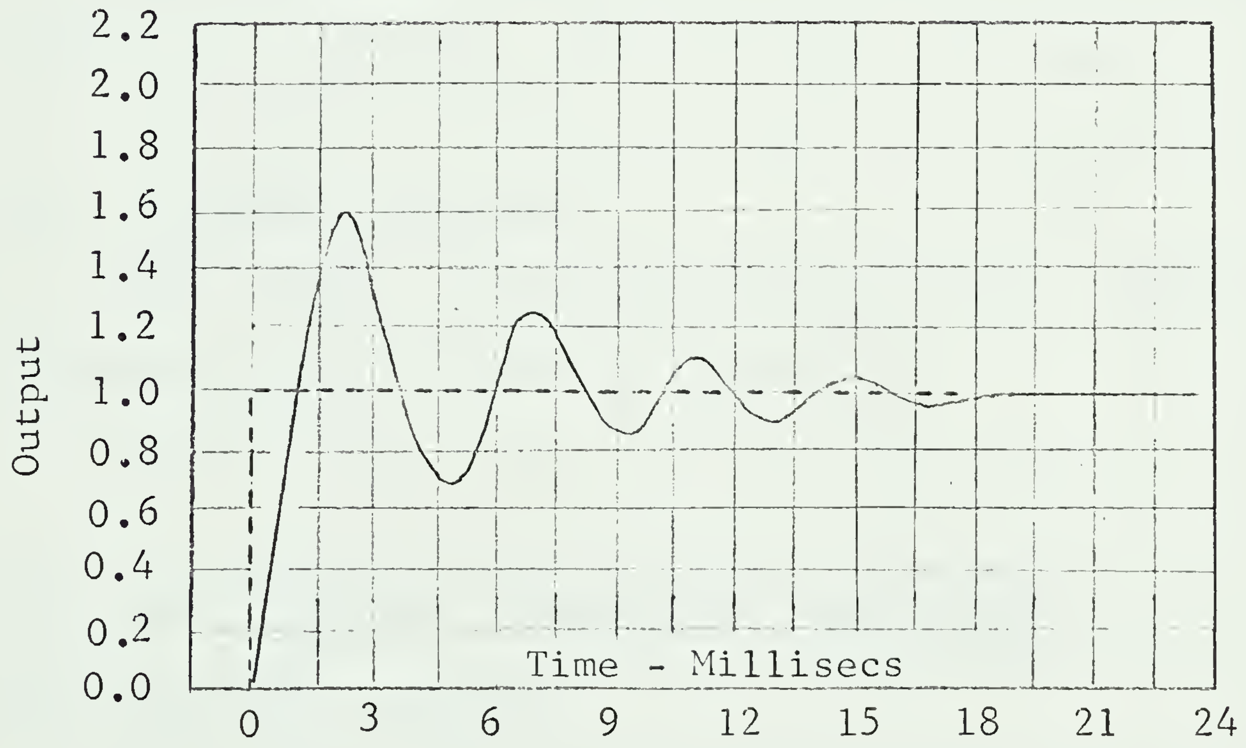


figure 17

TRANSIENT RESPONSE OF THE UNCOMPENSATED

POSITION CONTROL SYSTEM

(B) STEADY STATE ERROR

The steady state error for a step of R is given as follows:

$$Ess = \lim_{s \to o} E(s) \qquad = \frac{R}{1 + \lim_{s \to o} G(s)} \quad \ldots\ldots\ldots 5.1$$

$$Kp = \lim_{s \to o} G(s) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.2$$

$$Ess = \frac{R}{1 + Kp} = 0.5\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.3$$

where Kp is the positional error constant.

The steady state error was also measured experimentally and found to be 0.5 percent.

(C) BANDWIDTH

The bandwidth, with K_1 set to 0.5, was measured and found to be 320 hertz. An 11 db peak was evident at 200 hertz.

(D) FREQUENCY RESPONSE

The system, operated in the above mode, exhibited the frequency response shown in figure 15.

6.2 WITH POSITION FEEDBACK AND COMPENSATED

(A) TRANSIENT RESPONSE

The effect of the 5 hertz square wave of the closed loop system, shown in figure 11, is shown in figure 18. The gain K_1 was set to 0.5 and K_2 was set to 0.2.

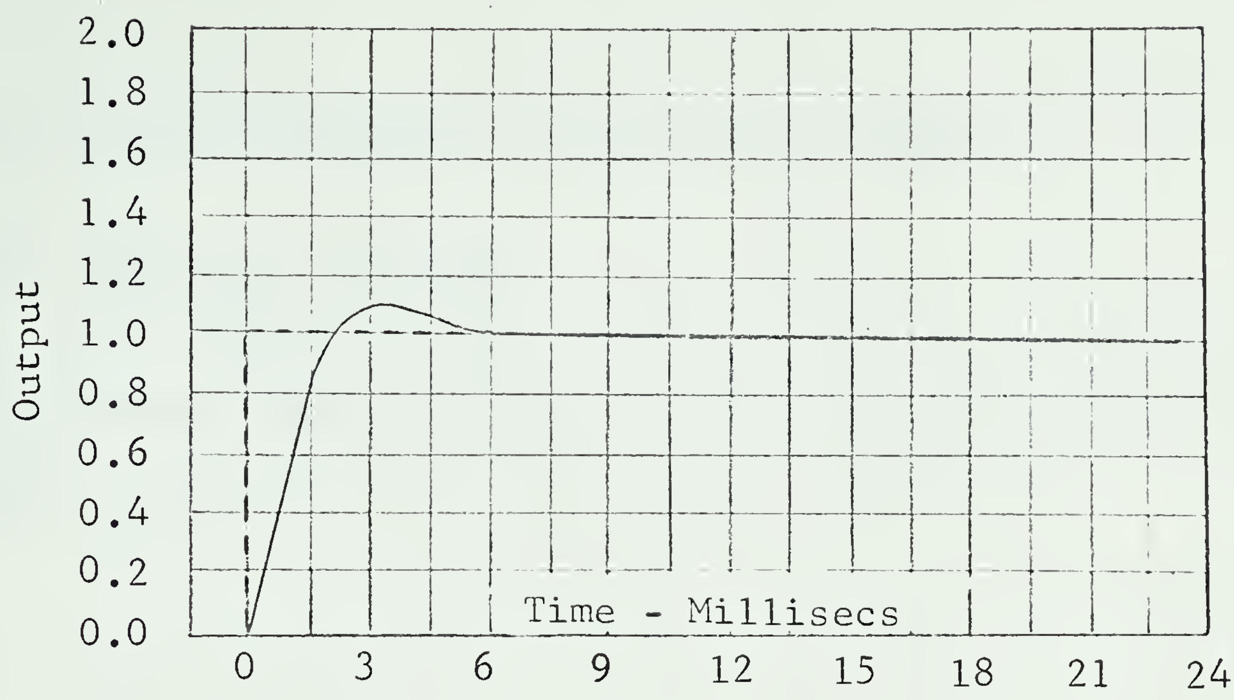


figure 18

TRANSIENT RESPONSE OF THE COMPENSATED POSITION CONTROL SYSTEM

(B) STEADY STATE ERROR

The steady state error was found to be the same as in the previous case.

(C) BANDWIDTH

The bandwidth, with the system operated in the above mode, was measured to be 320 hertz. No resonant peak was evident. The bandwidth can be increased by increasing the gain K_1; but a resonant peak will appear.

(D) FREQUENCY RESPONSE

The system, operated in the above mode, exhibited the position verus input voltage frequency response shown in figure 15.

6.3 MUSCLE COUPLED CASE WITH FORCE FEEDBACK

(A) TRANSIENT RESPONSE

The effect of the 5 hertz square wave, on the closed loop system shown in figure 16, is shown in figure 19. The gain K_1 was set to 0.15 and K_2 was set to 0.2.

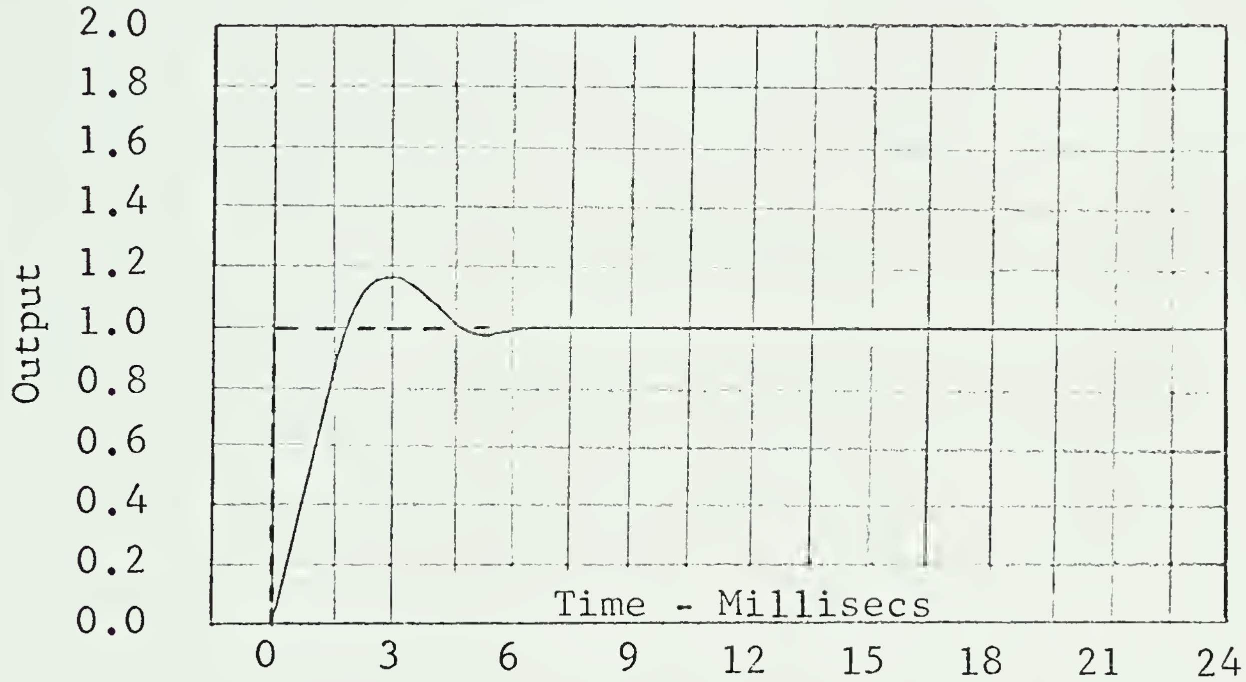


figure 19

TRANSIENT RESPONSE OF THE COMPENSATED SYSTEM WITH FORCE FEEDBACK

(B) STEADY STATE ERROR

The steady state error was calculated to be .93%, and experimentally measured to be .89%.

(C) BANDWIDTH

The bandwidth, with system operated in the above mode, was measured to be 280 hertz. A very small peak was evident.

The bandwidth can be improved by increasing the gain K_1, but an associated increase in the resonant peak will result.

(D) FREQUENCY RESPONSE

The system, operated in the above mode, exhibited the force verus input voltage frequency response shown in figure 15.

CONCLUSION

A comparison of the performance of the force control system with that of the device designed by Karpinski(2) illustrates a significant improvement. The steady state error has been decreased from 6 percent to 0.93 percent. The bandwidth has been increased to 280 hertz while maintaining a virtually flat force verus input voltage frequency response. A further increase in bandwidth is possible by increasing the pot K_1, but a resonant peak will result in frequency response. The frequency response of the device designed by Karpinski exhibited a 4 db resonant peak and bandwidth of 70 hertz.

Because both the input (position) and the output (force) were measured when the frequency response characteristics of the muscles were obtained, and the frequency response of the force transducer was flat in the applicable frequency range; the results shown in figure 14 are independent of the system characteristics. When comparing these results with the results obtained by Karpinski(2) for the same muscle and same initial prestretch it is apparent that the abrupt changes in magnitude and phase are no longer evident. Although only a limited number of muscles have been tested it is evident that his results were not completely independent of the system characteristics.

An additional feature, not existing in the previous design, is available with this apparatus. This feature

is the ability to operate in the positional feedback mode and to obtain a system performance independent of the muscle characteristics. This enables the position verus force transfer function of virtually any small muscle to be determined without additional system modification or compensation.

This apparatus has further application in muscle research where it is necessary to apply a constant force or velocity to the muscle. A constant force can be applied to the muscle by operating the system as a force control system and applying a D.C. signal to the input. By stimulating the muscle and causing it to contract, the position sensing unit can be monitored to study the velocity of contraction. Also by operating the system as a position control system and applying a ramp signal to the input, the muscle can be displaced with a constant velocity. The force exerted on the muscle during this displacement can be determined by monitoring the force transducer.

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APPENDIX I

The circuit diagram of the amplifier used to drive the force producing element is shown in figure A-1. The gain of this amplifier is 10.

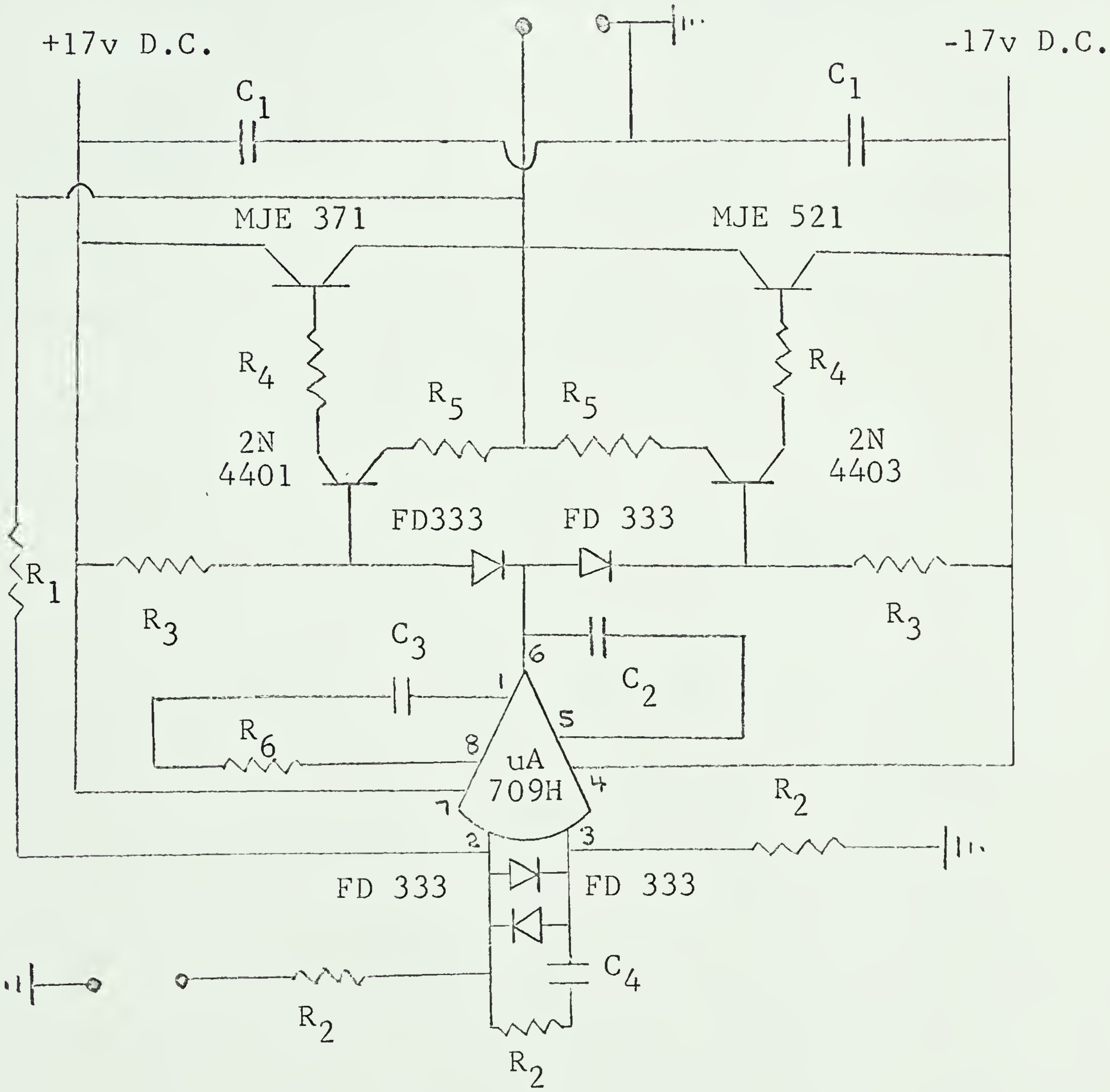

figure A-1

CIRCUIT DIAGRAM OF THE AMPLIFIER USED TO DRIVE THE FORCE PRODUCING ELEMENT

COMPONENT LIST

R_1 = 100 K	C_1 = .1 uf
R_2 = 10 K	C_2 = 5 pf
R_3 = 6.8 K	C_3 = 500 pf
R_4 = 22	C_4 = 200 pf
R_5 = 68	
R_6 = 1.5 K	

APPENDIX II

In addition to the driver amplifier, other amplifiers were used to process the system signals. These amplifiers, all incorporated on one circuit board, are described below and shown in the complete circuit diagram in figure A-5.

FORCE TRANSDUCER

The circuit diagram for the operational amplifier, used as the basis of the force transducer (figure 5), is shown in figure A-2.

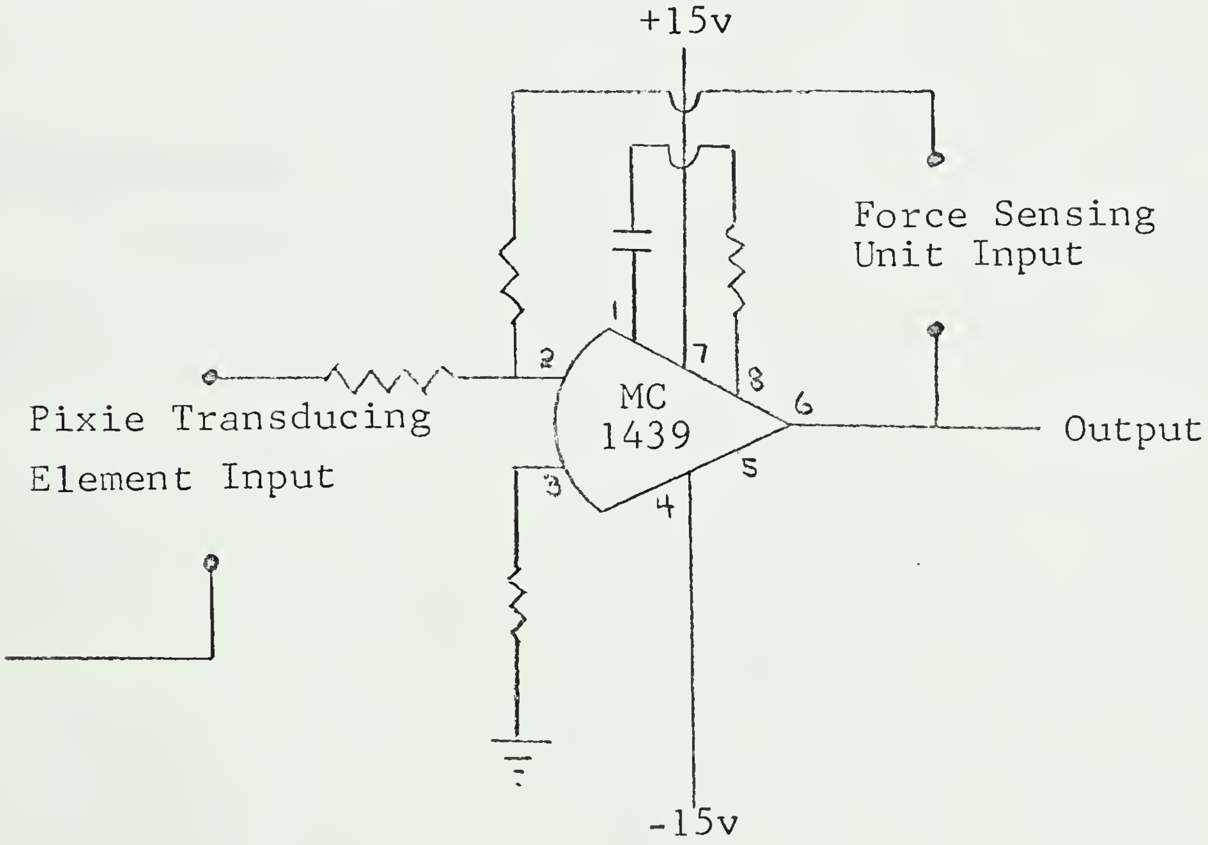

figure A-2

FORCE TRANSDUCER OPERATIONAL AMPLIFIER

SUMMATION

To sum the various system voltages the summer shown in figure A-3 was used.

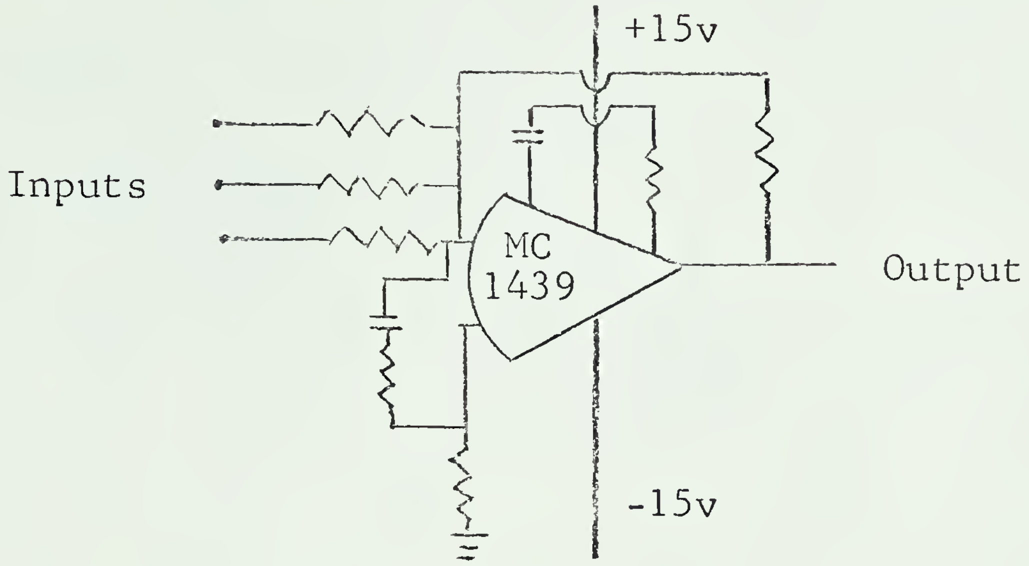

figure A-3

SYSTEM SUMMER

GAIN AMPLIFIER

To provide the necessary gain in the system the amplifier shown in figure A-4 was used.

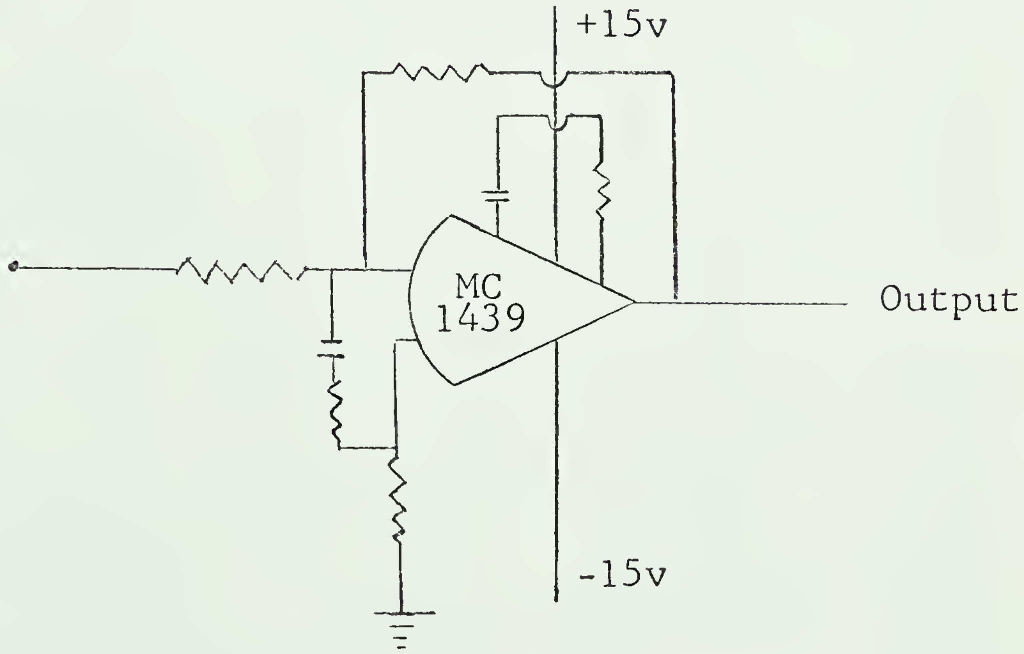

figure A-4

GAIN AMPLIFIER

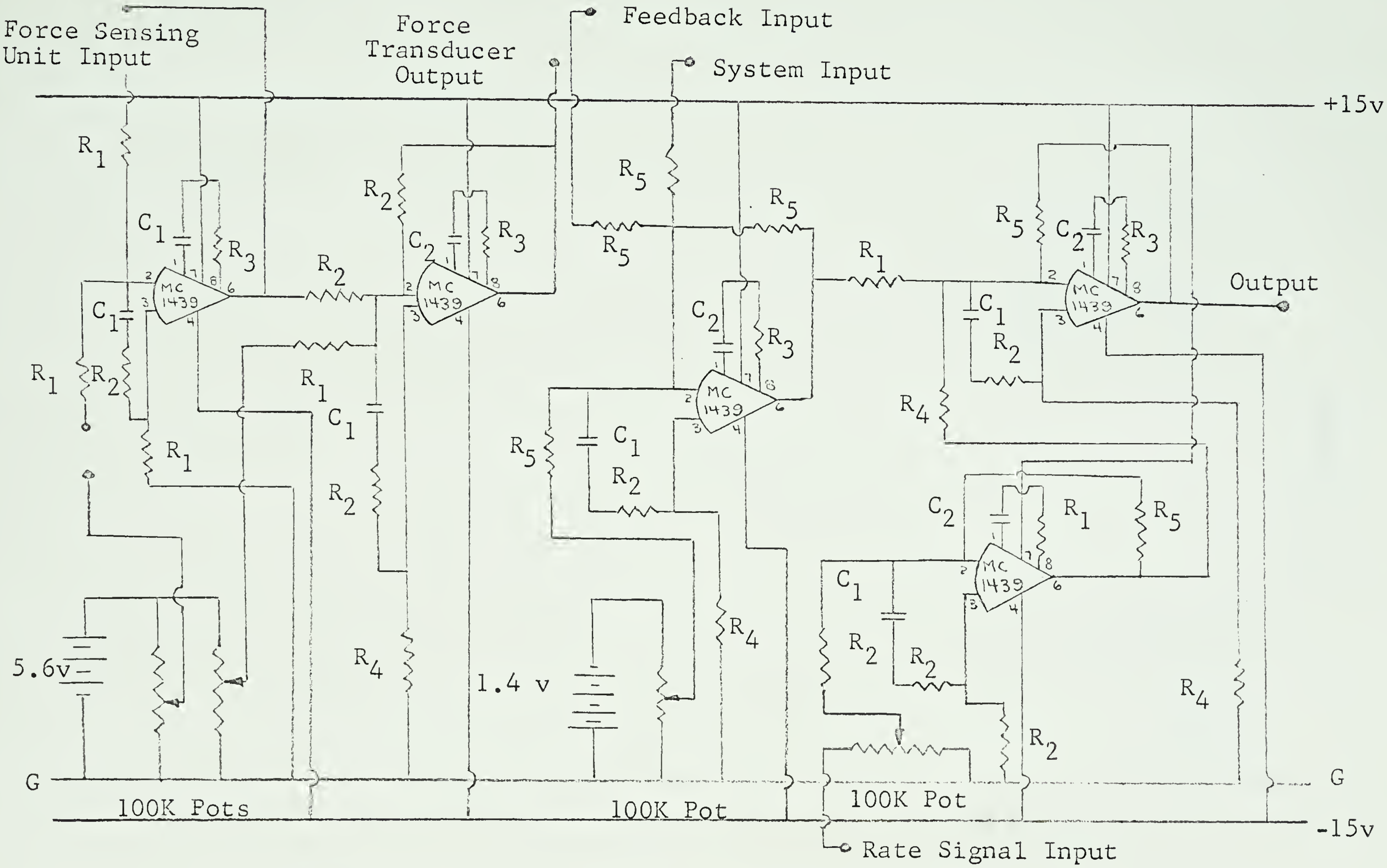

figure A -5 CIRCUIT DIAGRAM OF THE COMPLETE SYSTEM

COMPONENT LIST

R_1 = 1 K	C_1 = 250 pf
R_2 = 10 K	C_2 = 2200 pf
R_3 = 390	C_3 = .22 uf
R_4 = 4.7 K	
R_5 = 100 K	